

Evolution of Lithium-Beryllium-Boron and Oxygen in the early Galaxy

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Abstract

Oxygen is a much better evolutionary index than iron to describe the history of Lithium-Beryllium-Boron (LiBeB) since it is the main producer of these light elements at least in the early Galaxy. The O-Fe relation is crucial to the determination of the exact physical process responsible for the LiBeB production. At low metallicity, if [O/Fe] vs [Fe/H] is flat, then the production mode is independent of the interstellar metallicity, BeB is proportional to oxygen, i.e. is of primary nature. If not, the production mode is function of the progressive enrichment in O of the interstellar medium, BeB varies rather as the square of O, i.e. is of secondary nature. In the first case, fast nuclei enriched into He, C and O injected by supernovae and accelerated in surrounding superbubbles would explain the primary trend. In the second case, the main spallative agent would be the standard galactic cosmic rays. Calculated nucleosynthetic yields of massive stars, estimates of the energy cost of production of beryllium nuclei, and above all recent observations reported in this meeting seem to favor the primary mechanism, at least in the early Galaxy.

Key words: Cosmic Rays; Nucleosynthesis; Galactic Evolution; Light Elements

1 Introduction

Lithium-Beryllium-Boron take a special status in the general framework of nucleosynthesis. These nuclei, are indeed of exceptional fragility and they are destroyed in stars above about 1 million degrees. The only formation process available is spallation, i.e. fragmentation of medium light isotopes (CNO) leading to lighter species as ^6Li , ^7Li , ^9Be , ^{10}B and ^{11}B . Lithium is special since it is involved in both the thermonuclear fusion (Big Bang and AGB

stars and novae for 7Li), the neutrino spallation (7Li and ^{11}B can be synthesized through break up 4He and ^{12}C respectively) and nuclear non-thermal processes (both $^{6,7}Li$) Vangioni-Flam et al (1996). The other light isotopes are pure nuclear spallation products. The physical parameters of the spallation mechanism are fourfold: i) the production cross sections as a function of energy are fairly well measured in the laboratory ii) the source composition of the energetic component ii) the associated (injection) energy spectrum. iv) the target composition. In the following, we describe the two possible spallative processes able to produce LiBeB and we confront them to observational constraints. We show how the relation between oxygen and iron, in the halo phase is determining to discriminate between the two processes.

2 Spallation processes and astrophysical sites

The pioneering article of Meneguzzi, Audouze and Reeves (1971) offered the first quantitative explanation of the local abundances of LiBeB, at a time when only cumulated abundances in the solar system were available. The standard Galactic Cosmic Rays (GCR), essentially composed of fast protons and alphas collide with CNO nuclei sitting in the interstellar medium to yield measured LiBeB abundances. But the observed isotopic ratios of Li and B were not reproduced. A stellar source of 7Li was made necessary. For ^{11}B a complementary had hoc spallative source of low energy was invoked. Indeed, in this formulation evolution was ignored.

Introducing now the time parameter means to take into account the fact that the amount of CNO varies in the ISM as well as the flux of cosmic rays (protons and alphas) ϕ , presumably like the rate of supernovae, $dN(SN)/dt$, itself responsible for the increment of metallicity, we get the following equation:

$$d(L/H)/dt = z(t)\langle\sigma\rangle\phi(t)$$

where $z(t)$ is the evolving CNO fraction by number and $\langle\sigma\rangle$ is the production cross section averaged over the energy spectrum. Since z is proportional to $N(SN)$, integrating we get, assuming a constant spectral shape:

$$d(L/H)/dt \propto N(SN)dN(SN)/dt \text{ or } L/H \propto z^2$$

Then the abundance of a given light element increases like the square of the CNO abundance (or as a good approximation to O). Thus according to the classical tradition in galactic evolution, the production of LiBeB by the GCR is called "secondary".

In the nineties, measurements of Be/H and B/H from KECK and HST, to-

gether with [Fe/H] (for a report of observations see IAU Symposium 198, 2000) in very low metallicity halo stars came to set strong constraints on the origin and evolution of LiBeB isotopes. The evolution of BeB was suddenly uncovered over about 10 Gyr, taking [Fe/H] as an evolutionary index. The linearity between Be, B and iron came as a surprise since a quadratic relation was expected from the standard GCR mechanism. It was a strong indication that the standard GCRs are not the main producers of LiBeB in the early Galaxy. A new mechanism of primary nature was required to reproduce these observations: it has been proposed that low energy CO nuclei (a few tens MeV/n) produced and accelerated by massive stars (WR and SN II in superbubbles, i.e. cavities in the interstellar medium excavated by the winds and explosion of massive stars) fragment on H and He at rest in the ISM. This low energy component (LEC) has the advantage of coproducing Be and B in good agreement with the ratio observed in Pop II stars (see figure 1) (Vangioni-Flam et al 2000, Ramaty et al 2000). The corresponding equation is then:

$$d(L/H)/dt = n(H, He)\langle\sigma\rangle\phi(CO)(t)$$

where the first term is the concentration of H and He in the ISM, approximately constant, $\langle\sigma\rangle$ is the cross section averaged over the equilibrium (interstellar) spectrum, and $\phi(CO)(t)$ the flux of C and O nuclei, assumed to be proportional to the supernova rate. Owing to the constancy of the abundance of the target nuclei, the integration leads to a strict proportionality between the cumulated Be, B abundances and the metallicity. The LEC process is naturally called "primary".

Note that the two processes have in common the accelerating agents, namely the supernovae. In our opinion, they are not mutually exclusive but rather successive, the primary process being active in the halo phase and the secondary in the disk. The main differences are: i) The source composition of LEC, reflecting that of SN ejecta, is enriched into C, O and He. The richness in alpha particles, compared to the standard GCR ones, allows in particular a generous formation of 6Li (Vangioni-Flam et al 1999) which can be invoked to explain the abundance of this isotope in halo stars. ii) The form of the energy spectrum: LEC could have a different spectrum than GCR, since the conditions of acceleration in Superbubbles are different from those prevailing in the interstellar medium (Bykov 2000). The spectrum is predicted to be enriched in low energy particles. The mean energy of LEC, averaged on time being estimated to about 100 MeV/n (Bykov, private communication), whereas that of GCR is of the order of 1GeV/n. iii) Above all, they differ by the order of the production process, primary for LEC and secondary for standard GCR. Today, since data are available down to [Fe/H] = -3, the evolutionary models have not only to explain the cumulative abundances measured in the solar system but also the evolutionary trends.

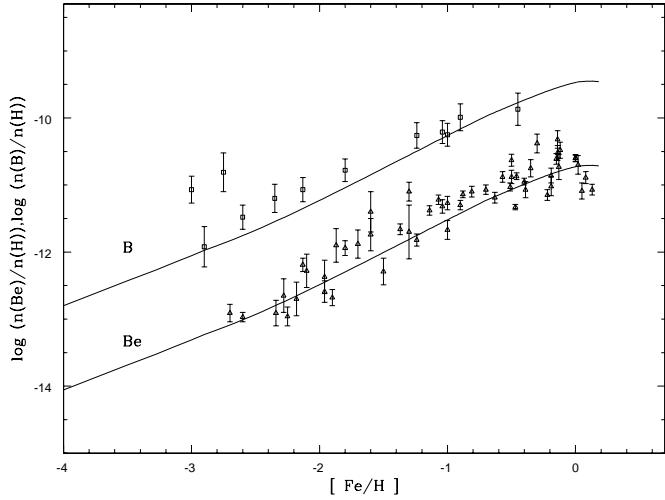


Fig. 1. Beryllium and Boron evolution vs $[Fe/H]$. The halo evolution is dominated by the LEC component (primary) emanating from supernovae. The contribution of the standard GCR component (secondary) is unsignificant below $[Fe/H] < -1$ if O is proportional to Fe, if not, i.e. $[O/Fe] \propto [Fe/H]$, the transition between primary and secondary processes could occur around $[Fe/H] = -2$, Vangioni-Flam et al 1998, Fields and Olive 1999.

The term "metallicity", up to now has been ambiguously defined. In fact, all the above argumentation assumes that CNO/Fe is constant at $[Fe/H]$ less than -1. Since oxygen is the main progenitor of BeB, the apparent linear relation between BeB and Fe could be misleading if O was not strictly proportional to Fe. Thus the pure primary origin of BeB in the early Galaxy could be questionned.

If O/Fe is constant, the GCR process is clearly negligible due to the paucity of the ISM in CNO, in the halo phase. The LEC process is obviously predominant, since it is free from the ISM metallicity, relying on freshly synthesized He, C, and O. Progressively, following the general enrichment of the ISM, GCR gain importance. Neutrino spallation plays its marginal role, increasing the abundance of ^{11}B .

Recent observations of Israelian et al (1998) and Boesgaard et al (1999) (IB) showing a neat slope in the O-Fe plot have seeded a trouble. If this trend is verified, the whole interpretation has to be modified, giving a larger role to the secondary process in the halo phase (Fields and Olive 1999). Nevertheless, even in this case, according the general consensus, the primary component is at least required in the very early Galaxy. However these observations are considered as controversial, and the whole session is centered on this point. What is the right O-Fe correlation? This point is crucial to translate the (Be, B) - Fe relations into (B, Be) - O ones. In the IB observations, $[O/Fe]=-0.35$

$[\text{Fe}/\text{H}]$, and consequently $\log(\text{Be}/\text{H})$ is proportional to $1.55 [\text{O}/\text{H}]$. Fields and Olive have used this relation to rehabilitate the classical standard GCR as the progenitor of LiBeB. But, beyond the observational questioning, this scenario meets with theoretical difficulties. The energy cost to produce a single Be nucleus is unfavorable but not prohibitive since this cost is plagued by large uncertainties (Fields et al 2001). Another difficulty is that the stellar supernova yields integrated in a galactic evolutionary model cannot fit the new O/Fe data ((?), F. Matteucci, this meeting). Moreover, the observational $[\alpha/\text{Fe}]$ vs $[\text{Fe}/\text{H}]$ where $\alpha = \text{Mg}, \text{Si}, \text{Ca}, \text{Ti}$ show a plateau from $[\text{Fe}/\text{H}] = -4$ to -1 . It would be surprising that oxygen does not follow the Mg, Si and Ca trends since all these nuclei are produced by the same massive stars. If the trend expressed in this meeting, namely $[\text{O}/\text{Fe}]$ is approximatively constant or slightly varying in the halo phase is confirmed, then the theoretical situation is clarified and the primary component made necessary in the early Galaxy, until $[\text{Fe}/\text{H}] = -1$.

3 Conclusion

The synthesis of LiBeB in the halo proceeds through nuclear spallation, essentially by the break up of oxygen. The observed relation between BeB and Fe has to be translated through the O - Fe relation into a BeB - O one which is representative of the relevant physical production process. And consequently the observational O - Fe relation is determining. (except if one succeeds to measure Be, B and O simultaneously in stars (A.M. Boesgaard and K. Cunha, this meeting)). Anyway the primary component is required in the halo phase, then afterwards the secondary process takes over; the question is therefore at which metallicity the transition occurs, this depends on the behaviour of $[\text{O}/\text{Fe}]$. To test in details the scenarios, the ideal would be to get the evaluation of O, Fe, Mg Be, B, Li abundances in the same stars. Impressive progress are waited from the VLT. Gamma ray line astronomy, through the european INTEGRAL satellite, to be lauched in 2002, will help to constrain the energy spectrum and intensity of LEC.

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